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Problems with the Current Cosmological Paradigm

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Abstract. We note that despite the apparent support for the ΛCDM model from the acoustic peaks of the CMB power spectrum and the SNIa Hubble diagram, the standard cosmological model continues to face several fundamental problems. First, the model continues to depend wholly on two pieces of undiscovered physics, namely dark energy and cold dark matter. Then, the implied dark energy density is so small that it is unstable to quantum correction and its size is fine-tuned to the almost impossible level of one part in $\approx 10^{102}$; it is also difficult to explain the coincidence between the dark energy, dark matter and baryon densities at the present day. Moreover, any model with a positive Λ also creates fundamental difficulties for superstring theories of quantum gravity. We also review the significant number of astrophysical observations which are now in contradiction with the ΛCDM model. On the grounds that the SNIa Hubble diagram is prone to evolutionary corrections and also that the CMB power spectrum may be contaminated by the effects of foreground ionised gas, we argue that the existence of such systematics could still allow more satisfactory, alternative, models to appear. We suggest that if $H_0 \lesssim 50\,\mathrm{kms^{-1}Mpc^{-1}}$ then a simpler, inflationary model with $\Omega_{baryon} = 1$ might be allowed with no need for dark energy or cold dark matter. We note that the clear scale error between HST Cepheid and Tully-Fisher galaxy distances and also potential metallicity dependencies for both the Cepheid P-L relation and the SNIa Hubble diagram may mean that such a low value of H_0 cannot yet be ruled out.

1. Introduction

It is a recurrent recent theme that we live in a 'New Age of Precision Cosmology' to the point where we may even be witnessing 'the end of cosmology'. These views are prompted by the cosmic microwave background anisotropy results from Boomerang and WMAP (Netterfield et al., 2002, Hinshaw et al., 2003) on the one hand and the SNIa Hubble Diagram results on the other (Riess et al., 1998, Perlmutter et al., 1999). These results both appear to indicate that the Universe is dominated by Cold Dark Matter and Dark Energy. But both fundamental and astrophysical problems for ΛCDM remain. These are significant enough to suggest that continued inspection of the current cosmological data for ways out of the current 'concordance' model may still be worthwhile. Here, after considering the fundamental problem areas for the standard model, we shall

look at the CMB and SNIa results which are the main observational pillars of the model and suggest that they may be more susceptible to systematic error than currently emphasised. This shall prompt us to look at alternative models which drop the assumption of either cold dark matter or dark energy or both.

2. A new age of precision cosmology?

The idea that the age of precision cosmology has dawned, is based on the Boomerang and WMAP CMB anisotropy experiments' detections of the first acoustic Doppler peak at $l = 220$ ($\approx$1-2 deg). Such a large spatial scale for the first peak is expected in a spatially flat, CDM Universe. The confirmation of the Boomerang results by the WMAP experiment has removed any doubt as to the observational reality of this detection. This observation is complemented by the evidence for an accelerated expansion seen in the SNIa Hubble Diagram. Jointly, these two observations appear to require a zero spatial curvature Universe with $\Omega_\Lambda = 0.7$ and $\Omega_m = 0.3$.

Although the argument for the standard model has undoubtedly been strengthened by the above two observations, fundamental problems still remain. For example, the standard ΛCDM model still relies on two pieces of undiscovered physics! The first is the CDM particle for which there is still no laboratory detection, some twenty years after it was first proposed (Blumenthal et al., 1982, Bond, Szalay & Turner, 1982, Peebles, 1982). For the optimists, the search for the CDM particle is likened to the search for the neutrino in the 1930's but for the pessimists the situation may be more like the search for the electro-magnetic ether at the end of the 19th Century. The second piece of undiscovered physics is dark energy. The invoking of dark energy also makes ΛCDM complicated and fine-tuned. There are two separate fine-tuning problems associated with dark energy, at least when it is represented as a cosmological constant. First, the vacuum energy term is small; after inflation it is only one part in 10^{102} of the energy density in radiation. This small size means that the dark energy is unstable to quantum correction (e.g. Dvali, Gruzinov & Zaldarriaga, 2003). Second, there is the coincidence that it is only relatively close to the present day where $\Omega_\Lambda \approx \Omega_m$; there seems no clear reason why the present day should have this special status. Even for those who dislike fine-tuning arguments, to start with one fine tuning (flatness) problem and end up with several seems circular!

Several solutions have been proposed to solve the Λ fine-tuning problems. For example, quintessence is the name given to the dark vacuum energy when it takes the form of a scalar field slowly rolling down a potential, usually from an initially high value, until the present day (Wetterich, 1988; Peebles & Ratra, 1988). Indeed, the initial value can be comparable to the radiation energy density after inflation, thus addressing the first Λ fine-tuning problem. However, it offers no solution to the second Λ fine-tuning problem of the coincidence with the matter energy-density at the present day.

Another solution is represented by the aptly-named Cardassian model (Chung & Freese, 2000, Freese & Lewis, 2002) where an extra term is added to the Friedmann equation so that $H^2 = A\rho + B\rho^n$, with $n < 2/3$. (A related model is the brane-induced gravity model of Dvali, Gabadadze & Porrati, 2000). The extra power-law term could arise from gravitational effects caused by embedding the

Universe as a 3(+1)-D brane in a higher dimensional entity. Here the accelerated expansion arises from the extra term associated with the matter density, ρ. This has the benefit of removing the need for dark vacuum energy and even cold dark matter and so could be said to reduce the dependence of the model on undiscovered physics. The removal of dark energy again addresses the first Λ problem but the second problem of why the acceleration only starts to dominate at the present day is again left unaddressed.

We note that a further problem has appeared for any model with a positive cosmological constant in that superstring theories of quantum gravity with compactified extra spatial dimensions are much more viable in models where $\Lambda < 0$ (Anti-de Sitter space) than in cosmologies where $\Lambda > 0$ (Banks, 2000, Witten, 2001, Deffayet, Dvali & Gabadadze, 2002). Although solutions have been suggested to this problem they appear highly contrived (Kachru et al., 2003). Thus there are many fundamental problems involved with the size and sign of the dark energy density required by the standard model. So unnatural does a small, positive cosmological constant appear to be that several authors have resorted to invoking the anthropic principle as the most likely hope for an explanation (Efstathiou, 1995, Martel, Shapiro & Weinberg, 1998).

Even without dark energy, further fundamental problems are inherent in any model based on CDM. First, as noted by Peebles (1984), any CDM model has some fine-tuning since $\Omega_{CDM} \approx \Omega_{baryon}$. Attempts have previously been made to explain this coincidence if the cold dark matter particle has approximately the mass of the proton (Turner & Carr, 1986, priv. comm.), but the accelerator lower limit on the mass of the neutralino, for example, is now an order of magnitude higher than this. Second, baryonic dark matter is needed anyway since nucleosynthesis implies that $\Omega_{baryon} \approx 10 \times \Omega_{star}$. The baryonic candidate for the $\Omega_0 \approx 0.1$ dark matter may then be a contender also for the $\Omega = 1$ dark matter candidate (see Section 5 below). Third, the dark matter in the Coma cluster has a significant baryon component with ≈20% of the virial mass of Coma now well known to be hot X-ray gas (Lea et al., 1973). The discovery of substantial amounts of X-ray gas in clusters such as Coma has reduced the Coma mass-to-light ratio from M/L≈60-600 to M/L≈5. If the Coma 'missing mass' problem is only at the level of M/L≈5 then it may be considered less plausible to invoke a cosmological density of exotic particles than if M/L≈60-600! If Zwicky had known about the X-ray gas in Coma, the question is whether he would have been inclined to introduce the term 'missing mass' at all!

3. Astrophysical problems for ΛCDM

There are several other problems for the ΛCDM model which might be classed more observational or astrophysical than fundamental. First, the mass profiles of low surface brightness galaxies appear to be less sharply peaked than predicted by CDM models (Moore et al, 1999a). Second, the large numbers of sub-haloes predicted in galaxy haloes may make spiral disks subject to tidal disruption on timescales of less than a Gigayear (Moore et al., 1999b). Third, the observed galaxy luminosity function is much flatter than the mass distribution predicted by CDM; attempts to suppress star-formation by invoking significant feedback

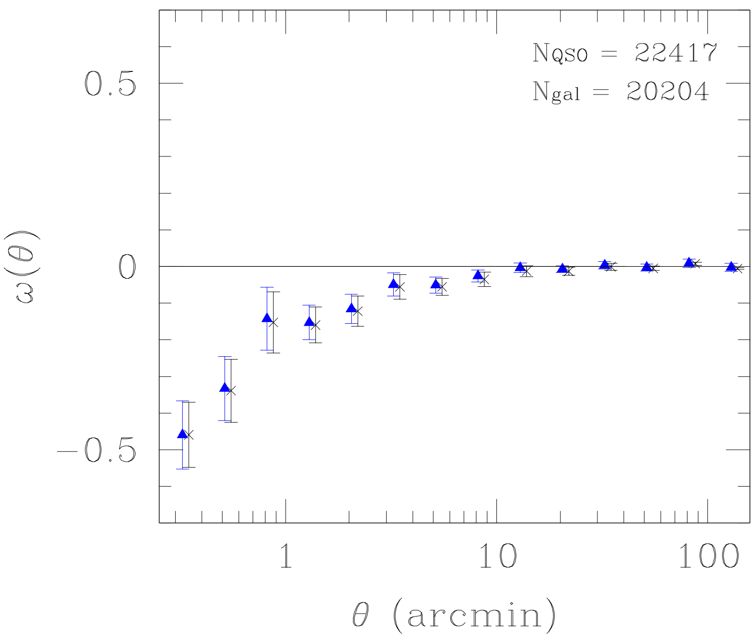

Figure 1. The 2-D spatial cross-correlation between QSOs and foreground APM/SDSS selected galaxy groups and clusters from Myers et al. (2003). The anti-correlation is the result expected if the foreground clusters are lensing the background QSOs in a high-density, $\Omega_m \approx 1$ Universe. The similarity of the results shown by the squares and triangles show the anti-correlation is robust to whether the search is made for QSOs around clusters or vice-versa.

in low-mass haloes appear to create further problems at higher masses (Benson et al., 2003). Fourth, the slope of the galaxy correlation function is flatter than predicted by ΛCDM, suggesting that the galaxy distribution must be anti-biased on scales $r < 1h^{-1}$Mpc. This means that a simple high peaks bias model is disallowed (Colin et al., 1999) - although this is not a problem in principle, it does mean that the bias model has to be relatively complicated. Fifth, the $L_X - T$ relation for galaxy clusters is not scale-free as predicted by hierarchical models (Lloyd-Davies et al. 2000). Some attempts have been made to fix things by suggesting that at small-scales, entropy might be increased by shocks created during the process of galaxy formation (Voit et al., 2003). However, the simpler explanation is that it is the mass distribution that is not scale free and this would represent a fundamental argument against hierarchical models such as ΛCDM.

Of course, any evidence that $\Omega_m \approx 1$ could be taken as evidence against the standard ΛCDM model which requires $\Omega_m \approx 0.3$. One such piece of evidence comes from the lensing of background QSOs in the 2dF QSO redshift survey by foreground galaxy groups and clusters (Croom & Shanks 1999, Myers et al., 2003). These authors find a high lensing mass per cluster which leads to a 2σ rejection of the $\Omega_m = 0.3$ model.

Evidence for $\Omega_m \approx 1$ even arises from the space abundances of galaxy clusters (Eke et al., 1998, Vauclair et al., 2003). The evolution of clusters is often quoted as vital evidence for the concordance model. But many of these estimates seem remarkably close to $\Omega_m = 1$. Vauclair et al. claim that the data support $0.8 < \Omega_m < 1$. The best estimate of Eke et al. is $\Omega_m = 0.45 \pm 0.25$. Even in the latter case, it might be recalled Guth (1981) argued that the $\Omega_m > 0.01$ lower limit from nucleosynthesis left Ω_m embarassingly close to unity and now even the estimate of Eke et al. lies within a factor of two of the Einstein-de Sitter value.

4. Escape routes: SNIa evolution + CMB foreground contamination

Given this collection of fundamental and astrophysical problems, it is worthwhile considering if there are any escape routes from the observations that underpin standard model. The escape route from the SNIa Hubble diagram is certainly clear; there is the obvious possibility that the SNIa maximum luminosity evolves with look-back time in a way that is not detectable in the SNIa spectra. The SNIa are ≈0.5mag fainter at z≈0.5 if $\Omega_\Lambda = 0.7$ and $\Omega_m = 0.3$ than in the Einstein-de Sitter case. Quite natural evolutionary mechanisms for SNIa certainly exist. For example, the metallicity of the SNIa progenitor stars at high redshift are likely to be lower than they are locally. Also the C/O abundance ratio of the White Dwarf will change as it awaits the accretion of mass which will trigger the explosion. These evolutionary corrections are likely to be comparable to the above effect of q_0 (Hoeflich et al., 2000).

In the case of the CMB power spectrum, the main escape route here is likely to be the CMB foregrounds. Although there are now quite good constraints from the CMB spectral index on contamination from Galactic synchrotron and dust, the WMAP results have suggested two other sources of foreground contamination. The excess TE polarisation detected by WMAP at large angular scales is interpreted as strong evidence for an early epoch of reionisation at $10 < z < 20$ with optical depth, $\tau \approx 0.17$ (Kogut et al., 2003). Homogeneous reionisation with this optical depth reduces the amplitude of the temperature power spectrum peaks by ≈30%. Inhomogeneous reionisation could also alter the peak shapes. Although this is expected only to affect the smaller peaks, the large-scale peaks could also be affected, depending on the model and the details of the reionisation process.

Another source of foreground contamination could be due to the SZ effect. Myers et al. (2004) have cross-correlated the Abell $R \geq 2$, $|b| > 40\,\mathrm{deg}$, clusters with the WMAP 94GHz W band data and found signifiant anti-correlation which they interpret as due to the SZ effect. Similar signals were found in the groups and clusters detected in the APM and 2MASS catalogues. Interestingly, they found that in the case of the rich clusters the anti-correlation appeared to extend to scales larger than the $12.'6$ W-band beam size, out to scales of $\approx 1\,\mathrm{deg}$ ($\approx 5\mathrm{h}^{-1}\mathrm{Mpc}$) which could be caused by ionised supercluster gas. Although the significance of the extended signal is lower than on the beam-size, if it is real then there could be important implications. In particular, there could be a significant SZ contribution to even the first peak of the power spectrum on $\approx 1 - 2\,\mathrm{deg}$ scales. Thus on grounds of both the ionised gas at the epoch of

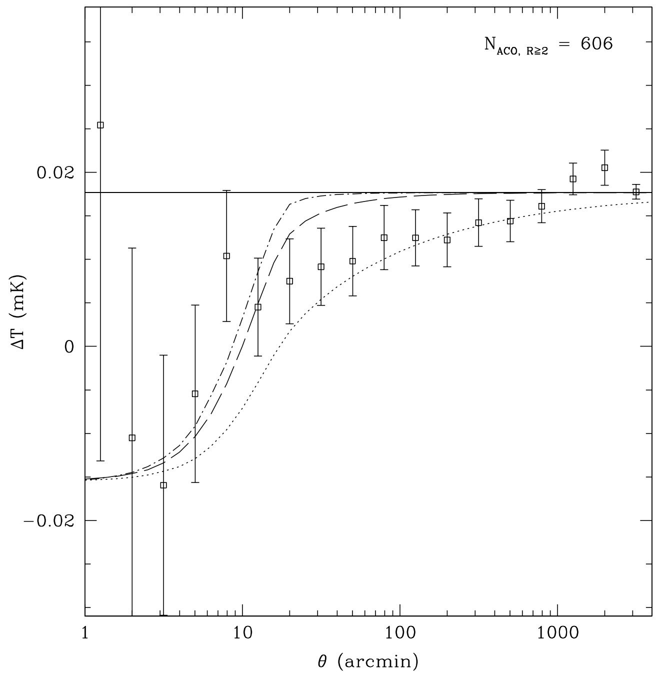

Figure 2. Cross-correlation of WMAP 94 GHz W band data with ACO $R \geq 2$ Abell clusters for combined ACO $|b| > 40$ deg N+S samples. The dashed, dotted and dot-dash lines are isothermal models for the SZ decrement as presented by Myers et al. (2004).

reionisation at $z \approx 15$ and the hot gas in clusters at lower redshift, the CMB signal may have come through more foreground 'traffic' than previously expected and the resulting contamination may have seriously compromised its primordial signal.

5. H_0 route to a simpler model

Given that the quintessence and Cardassian modifications to the standard model only represent partial solutions to the problems of dark energy and dark matter we next consider a previously suggested route via H_0 to a simpler model. Shanks (1985, 1991, 1999, 2000, 2002) suggested that if $H_0 \lesssim 30\mathrm{kms}^{-1}\mathrm{Mpc}^{-1}$ then there might be no need to introduce either dark matter or dark energy. With a low value of H_0, an inflationary model with Ω_{baryon}=1 is then better placed to escape the baryon nucleosynthesis constraint, since $\Omega_0 = \rho_0/\rho_c$ and $\rho_c = 3{H_0}^2/8\pi G$. Simultaneously, the low value of $\mathrm{H_0}$ means that the X-ray gas in the Coma cluster increases towards the Coma virial mass, since $M_{gas}/M_{virial} \propto {H_0}^{-1.5}$. Finally, the lifetime of an Einstein-de Sitter Universe increases as $1/H_0$ to become compatible with the ages of the oldest stars. Given the historical uncertainty there has been in observational estimates of $\mathrm{H_0}$, the potential simplification in cosmology that this very simple model offers, removing the need for dark energy and cold dark matter, provides clear motivation to continue to investigate the distance scale and Hubble's constant.

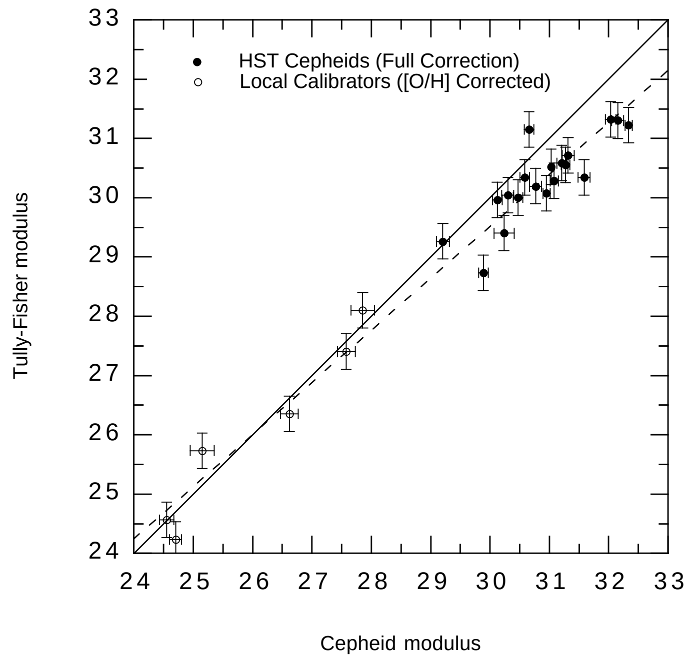

Figure 3. Tully-Fisher versus metallicity/incompleteness corrected HST Key Project Cepheid distances (Allen & Shanks, 2004). The TF relation underestimates Virgo galaxy distances by 34±6%. The least squares fit (dashed line) shows 3.5σ evidence for a TF scale error.

The value of Hubble's constant has been notoriously difficult to estimate. prior to the opening of the Palomar 5-m telescope in 1950, Hubble's value was $H_0 \approx 500\,\mathrm{kms^{-1}Mpc^{-1}}$. Since then, estimates of H_0 have moved down to $H_0 \approx 70\,\mathrm{kms^{-1}Mpc^{-1}}$. We now argue that the value of H_0 may fall yet further.

Some 25 galaxies have had Cepheids detected by HST. Seventeen of these were observed by the HST Distance Scale Key Project (Freedman et al., 1994, Ferrarese et al., 2000). Seven were observed in galaxies with SNIa by Sandage and collaborators (eg Sandage et al., 1996) and M96 in the Leo I Group was observed by Tanvir et al. (1995). Allen & Shanks (2004) have used these data to update the comparison of I-band Tully-Fisher (TF) distances of Pierce & Tully (1992) with the published HST Cepheid distances. These authors find that TF distance moduli at the Virgo distance are underestimates by ≈22±5%. If the Key Project metallicity correction (see also Hoyle, Shanks & Tanvir, 2003) and the P-L incompleteness correction of Allen & Shanks is applied to the Cepheids then the TF moduli at the Virgo distance are now underestimates by 34±6% (see Fig. 3). This reduces Tully-Fisher estimates of $\mathrm{H_0}$ from ≈85 to ≈65$\mathrm{kms^{-1}Mpc^{-1}}$ (Giovanelli et al., 1997, Shanks 1997, Shanks, 1999, Sakai et al., 1999). Of course, H_0 might be further reduced if the TF scale error persists to Coma. The correlation of Cepheid residuals with line-width suggests TF distances may be Malmquist biased - possibly implying a bigger TF scale error at larger distances. This clear problem for TF distances, which previously has been the 'gold standard' of secondary distance indicators, warns that errors in the extragalactic distance scale may still be seriously underestimated!

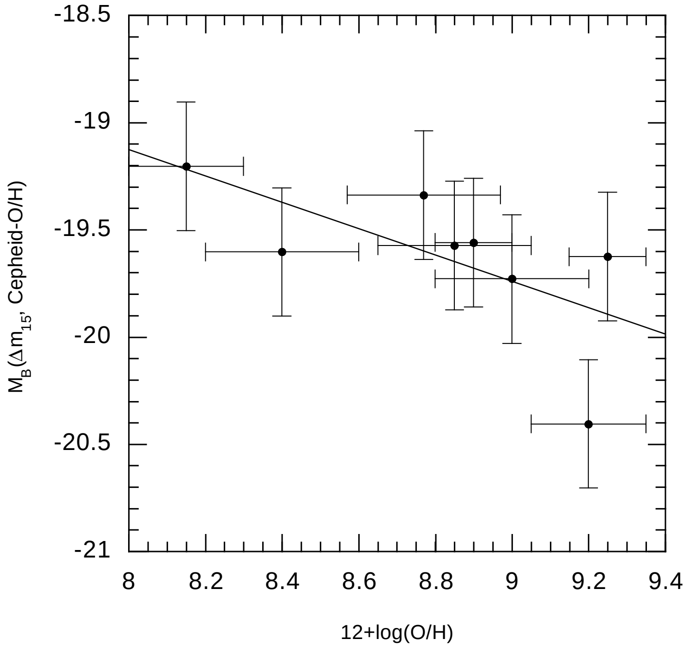

Figure 4. The SNIa absolute magnitude-metallicity relation using the SNIa peak magnitudes of Gibson et al. (2000), now corrected for Δm_{15} and Cepheid metallicity/incompleteness (Allen & Shanks 2004). The least squares fit (solid line) shows 2σ evidence for a correlation.

Eight HST Cepheid galaxies also have SNIa distances. Correcting the Cepheid scale for metallicity and incompleteness bias after Allen & Shanks and then using these distances to derive peak luminosities using the SNIa data from Gibson et al. (2000) implies a possible correlation between Type Ia peak luminosity and metallicity (see Fig. 4). Such a scatter in SNIa luminosities could easily be disguised by magnitude selection (Malmquist) effects at moderate redshifts. At higher redshift the correlation is in the right direction to explain away the need for a cosmological constant in the Supernova Hubble Diagram results, since galaxies at high redshift might be expected to have lower metallicity. Thus the conclusion is that if Cepheids have strong metallicity dependence then so have SNIa and therefore SNIa estimates of q_0 and H_0 may require significant correction.

6. Conclusions

Our main conclusions are as follows:-

- ΛCDM gains strong support from the WMAP and Boomerang CMB peaks and also the SNIa Hubble diagram - but leaves a standard model which is fine-tuned to the almost impossible level of one part in 10^{102} and based on two pieces of undiscovered physics, dark energy and cold dark matter.
- The size of the vacuum energy density implied by the SNIa Hubble diagram is so small that it is unstable to quantum corrections.

- Superstring models of quantum gravity which invoke compactified higher spatial dimensions are broadly incompatible with the positive cosmological constant of the ΛCDM model and prefer models with negative or no cosmological constant.

- ΛCDM also has astrophysical problems predicting galaxy mass profiles that are too cuspy at small scales and a galaxy luminosity function that is too steep. The model also has a problem with new results from QSO lensing that prefer a value of $\Omega_m \approx 1$.

- The main escape routes to other models include the expectation that the SNIa Hubble diagram may require evolutionary corrections. Further, the precision of the CMB power spectrum may still be compromised by foreground contamination from the epoch of reionisation at $z \approx 15$ and the SZ signal from galaxy clusters at $z \lesssim 1$.

- We have argued that if $H_0 \lesssim 50\,\mathrm{kms}^{-1}\mathrm{Mpc}^{-1}$ then it might allow a simpler, inflationary model with $\Omega_{baryon} = 1$ and with no need to invoke dark energy or cold dark matter.

- The strong scale error between HST Cepheid and TF distances and the potential metallicity dependencies for the maximum luminosity of SNIa and the Cepheid P-L relation suggests that there may still be systematic errors in the distance scale which may allow a significantly lower value of H_0; our very simple model with $\Omega_{baryon} = 1$ may therefore still not be ruled out.

Finally, we note that the fundamental weaknesses of the standard model make the conclusion that the Universe is CDM and dark energy dominated also vulnerable to the new higher-dimensional ‘brane-world’ cosmologies motivated by string theories (Randall & Sundrum 1999, Dvali, Gabadadze & Porrati, 2000, Freese & Lewis, 2002). These cosmologies offer a rich, new variety of terms to add to the standard Friedmann solution of the field equations. The resulting increased flexibility in observational cosmology will at least increase the chance of finding alternative cosmologies to ΛCDM. For example, there exist Cardassian models that fit the current CMB and SNIa data, assuming a baryon-dominated model. This model is still highly finely-tuned but no more than ΛCDM. Thus whether the increased flexibility in observational cosmology arises from this route or from the presence of systematic errors in the current cosmological data as argued here, it seems likely that a more satisfactory model than ΛCDM will at some stage appear and therefore that the rumours of the ‘end of cosmology’ may well be premature!

References

Allen, P.D. & Shanks, T. 2004, MNRAS accepted, astro-ph/0102447.

Banks, T. 2000, hep-th/0007146.

Bond, J.R., Szalay, A.S. & Turner, M.S., 1982, Phys. Rev. Lett. 48, 1636.

Benson, A.J., Bower, R.G., Frenk, C.S., Lacey, C.G., Baugh, C.M. & Cole, S.M. 2003, ApJ, 599, 38.

Blumenthal, G.R., Pagels,H., & Primack, J.R., 1982, Nature, 299, 37.

Chung, D.J.H. & Freese, K., 2000, Phys. Rev. D, 61, 023511.

Colin, P., Klypin, A.A., Kravtsov, A.V. & Khokhlov, A.M., 1999, ApJ, 523, 32.

Croom, S.M. & Shanks, T., 1999, MNRAS, 307, L17.

Deffayet, C., Dvali, G. & Gabadadze, G., 2002, Phys. Rev. D, 65, 044023.

Dvali, G., Gabadadze, G., Porrati, M., 2000, Phys. Lett., B485, 202.

Dvali, G. Gruzinov, A. & Zaldarriaga, M. 2003, Phys. Ref. D, 68, 024012.

Efstathiou, G., 1995, MNRAS, 274, L73.

Eke, V.R., Cole, S.M., Frenk, C.S. & Patrick, H.J. 1998, MNRAS, 298, 1145.

Ferrarese, L. et al., 2000, ApJS, 128, 431.

Freedman, W. L. et al., 1994, ApJ, 427, 628.

Freese, K. & Lewis, M., 2002, Phys. Lett., B540, 1.

Gibson, B.K. et al., 2000, ApJ, 529, 723.

Giovanelli, R., Haynes, M.P., da Costa, L.N., Freudling, W., Salzer, J.J., Wegner, G., 1997, ApJ, 477, L1.

Guth, A.H., 1981, Phys. Rev. D, 23, 347.

Hinshaw, G. et al., 2003, ApJS, 148, 63.

Hoeflich, P., Nomoto, K., Umeda, H. & Wheeler, J.C. 2000, ApJ, 528, 590.

Hoyle, F., Shanks, T. & Tanvir, N.R., 2003, MNRAS, 345, 269.

Kachru, S., Kallosh, R., Linde, A., & Trivedi, S.P., 2003, Phys. Rev. D, 68, 046005.

Kogut, A. et al., 2003, ApJS, 148, 161.

Lea, S.M., Silk, J., Kellogg, E. & Murray, S., 1973, ApJ, 184, L105.

Lloyd-Davies, E.J., Ponman, T.J. & Cannon, D.B., 2000, MNRAS, 315, L689.

Martel, H., Shapiro, P.R., Weinberg, S. 1998, ApJ, 492, 29.

Moore, B., Quinn, T., Governato, F., Stadel, J., & Lake, G., 1999a, MNRAS, 310, 1147.

Moore, B., Ghigna, S., Governato, F., Lake, G., Quinn, T., Stadel, J. & Tozzi, P., 1999b, ApJ, 524, 19.

Myers, A.D., Outram, P.J., Shanks, T., Boyle, B.J., Croom, S.M., Loaring, N.S., Miller, L. & Smith, R.J. 2003, MNRAS, 342, 467.

Myers, A.D., Shanks, T., Outram, P.J., Frith, W.J. & Wolfendale, A.W. 2004, MNRAS 347, L4. (astro-ph/0306180)

Netterfield et al., 2002, ApJ, 571, 604.

Peebles, P.J.E., 1982, ApJ, 263, L1.

Peebles, P.J.E., 1984, ApJ, 284, 439.

Peebles, P.J.E. & Ratra, B. 1988, ApJ, 325, L17.

Perlmutter, S., et al., 1999, ApJ, 517, 565

Pierce, M.J. & Tully, R.B., 1992 ApJ, 387, 47.

Randall, L. & Sundrum, R., 1999, Phys. Rev. Lett., 83, 3370.

Riess, A.G. et al., 1998, ApJ, 116, 1009.

Sakai, S. et al., 1999, ApJ, 523, 540.

Sandage, A.R., Saha, A., Tammann, G. A., Labhardt, L., Panagia, N., Macchetto, F. D., ApJ, 1996, 460, L15.

Shanks, T., 1985, Vistas in Astronomy, 28, 595.

Shanks, T. et al., 1991, In 'Observational Tests of Cosmological Inflation', Eds. Shanks, T., Banday, A.J., Ellis, R.S., Frenk, C.S. & Wolfendale, A.W. pp. 205-210 Dordrecht:Kluwer.

Shanks, T., 1997, MNRAS, 290, L77.

Shanks, T., 1999, In 'Harmonising Cosmic Distance Scales', eds Egret D. & Heck, A., PASP, pp. 230-234.

Shanks T. et al., 2000, In 'New Cosmological Data and the Values of the Fundamental Parameters,' IAU. Symp. 201, eds. Lasenby, A.N. & Wilkinson, A., ASP, in press.

Shanks, T., Allen, P.D., Hoyle, F. & Tanvir, N.R. 2002, In 'A New Era in Cosmology', eds. Metcalfe, N. & Shanks, T., ASP Conf. Ser., Vol. 283, pp. 274-279.

Tanvir, N. R., Shanks, T., Ferguson, H.C. & Robinson, D.R.T. 1995, Nature, 377, 27.

Vauclair, S.C., Blanchard, A., Sadat, R., Bartlett, J.G., Bernard, J.-P., Boer, M., Giard, M., Lumb, D.H., Marty, P. & Nevalainen, J. 2003, A&A, 412, L37.

Voit, G.M., Balogh, M.L., Bower, R.G., Lacey, C.G. & Bryan, G.L. 2003, ApJ, 593, 272.

Wetterich, C., 1988, Nucl. Phys. B302, 645.

Witten, E., 2001, in The Strings 2001 Conference, Tata Institute, Mumbai, India, http://www.theory.tifr.res.in/strings/